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U-Spin Symmetry in Doubly Cabibbo-Suppressed Charmed Meson Decays[1]

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ABSTRACT

We propose tests of U-spin symmetry in doubly Cabibbo-suppressed (DCS) charmed meson decays, $D^{0,+} \to K\pi$, $D_s^+ \to KK$, in decays to pairs of a vector and a pseudoscalar meson, and in decays to pairs of two vector mesons. U-spin breaking in relative phases between Cabibbo-favored (CF) and DCS amplitudes affects time-dependent studies of $D^0 - \overline{D}^0$ mixing. Comparison of final state phase patterns in DCS and CF amplitude triangles, which can shed some light on these phases, is carried out in a phenomenological framework incorporating resonance contributions.

Recently the CLEO Collaboration reported a measurement of the doubly Cabibbo-suppressed (DCS) decay $D^0 \to K^+\pi^-$ [1]. The measured branching ratio, based on a time-dependent rate measurement, is a substantial advance in sensitivity and is considerably lower than the previous world average [2]. The new world average [3] (we use $\tan\theta_c = 0.2256 \pm 0.0024$)

$$\frac{\mathcal{B}(D^0 \to K^+\pi^-)}{\mathcal{B}(D^0 \to K^-\pi^+)} = (1.47 \pm 0.31)\tan^4\theta_c \quad , \tag{1}$$

is consistent at 90% confidence level with flavor SU(3) symmetry, which predicts a value of $\tan^4\theta_c$ for the ratio of branching ratios [4].

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Early predictions based on factorization [5], in which several SU(3) breaking effects were claimed to accumulate, were larger than the SU(3) limit by a factor of about two to three. An uncertain factor in this estimate is the ratio of form factors $F_0^{DK}/F_0^{D\pi}$ at low q^2, which was taken to be smaller than one, whereas a value slightly larger than one is preferred on theoretical grounds. The present average value obtained from four experiments [6] is $F_0^{DK}(0)/F_0^{D\pi}(0) = 1.00 \pm 0.08$. The central value implies a factorization prediction of $1.72 \tan^4 \theta_c$ which is consistent with (1). However, the use of factorization in D decays has been frequently questioned, most recently in [7], where nearby resonances at 1430 and around 1800−1900 MeV were shown to contribute sizably to $D^0 \to K^-\pi^+$ [8].

SU(3) was observed to be badly broken in several singly Cabibbo-suppressed $\Delta S = 0$ D decays [9]. This includes the ratio of amplitudes [10] $\sqrt{2}|A(D^+ \to \pi^+\pi^0)|/|A(D^+ \to \overline{K}^0\pi^+)| = (1.78 \pm 0.26)\tan\theta_c$, which is expected to be $\tan\theta_c$ in the SU(3) limit. Since this ratio consists of decay amplitudes to exotic final states involving $\pi\pi$ in $I = 2$ and $K\pi$ in $I = 3/2$, it demonstrates that SU(3) breaking is not due only to resonance contributions. An interesting question is whether SU(3) breaking in DCS $\Delta S = -\Delta C$ processes, which do involve resonances, is in general smaller than in $\Delta S = 0$ decays, as seems to be the case in (1). We will study this question in the presence of resonance contributions.

The question of SU(3) breaking in DCS charmed meson decays plays an important role in time-dependent studies of $D^0 - \overline{D}^0$ mixing. Interference between mixing and decay to "wrong sign" $K\pi$ depends on the strong phase difference δ between the amplitudes of $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$ [11]. *A priori* knowledge of δ would simplify the analysis considerably [12]. This phase vanishes in the flavor SU(3) limit [4, 13]. Theoretical estimates of δ, based on various assumptions about SU(3) breaking, are strongly model-dependent [14]. Therefore, one seeks model-independent information about this phase, or about any other relative strong phase between corresponding DCS and CF D^0 decay amplitudes.

In the present Letter we study various tests of SU(3) symmetry in DCS charmed meson decays. We propose a variety of U-spin relations between decay rates which can test the validity of this symmetry [15, 16]. U-spin breaking would violate these relations, and could modify the final-state phase pattern of DCS processes relative to that of CF decays. A comparison of these two patterns is shown to indirectly shed light on the magnitude of relative final state phases between CF and DCS amplitudes. We study these patterns within a phenomenological framework which incorporates resonant contributions in an SU(3) breaking fashion. Using a range of SU(3) breaking parameters, we show that the phase δ can be as large as about 20 degrees. We point out certain experimental difficulties in measuring final state phases in DCS decays.

The presence of non-trivial relative phases between the amplitudes contributing to certain CF D meson decays can be ascertained by constructing amplitude triangles based on experimentally observed decay rates. The subprocess $c \to su\bar{d}$ involves a $\Delta I = 1$ transition. The amplitudes of the three two body decays $D^0 \to K^-\pi^+$, $D^0 \to \overline{K}^0\pi^0$, and $D^+ \to \overline{K}^0\pi^+$ are governed by two isospin amplitudes corresponding to $I = 1/2$ and $I = 3/2$ final states. Thus, the square roots of the corresponding rates form a triangle

$$A(D^0 \to K^- \pi^+) + \sqrt{2} A(D^0 \to \overline{K}^0 \pi^0) = A(D^+ \to \overline{K}^0 \pi^+) \quad . \tag{2}$$

Similar triangle relations hold in quasi two-body decays into a vector and a pseudoscalar meson:

$$A(D^0 \to K^{*-} \pi^+) + \sqrt{2} A(D^0 \to \overline{K}^{*0} \pi^0) = A(D^+ \to \overline{K}^{*0} \pi^+) \quad , \tag{3}$$

$$A(D^0 \to \rho^+ K^-) + \sqrt{2} A(D^0 \to \rho^0 \overline{K}^0) = A(D^+ \to \rho^+ \overline{K}^0) \quad , \tag{4}$$

and for partial-wave amplitudes A_l in decays to two vector mesons:

$$A_l(D^0 \to K^{*-} \rho^+) + \sqrt{2} A_l(D^0 \to \overline{K}^{*0} \rho^0) = A_l(D^+ \to \overline{K}^{*0} \rho^+) \quad , \tag{5}$$

where relations hold separately for S, P and D-waves.

If a triangle has non-zero area, the two corresponding isospin amplitudes have a non-trivial phase with respect to one another. Using experimental data, $I = 1/2$ and $I = 3/2$ amplitudes were shown [17, 18] to have relative phases close to 90° for the decays $D \to \overline{K}\pi$ and $D \to \overline{K}^*\pi$, but near zero for $D \to \rho\overline{K}$.

The isospin decomposition in DCS $\Delta S = -\Delta C$ processes differs from that in CF $\Delta S = \Delta C$ decays. In the former case the quark subprocess $c \to du\bar{s}$ involves both $\Delta I = 0$ and 1 transitions which yield three isospin amplitudes for $I = 1/2$ and $I = 3/2$ final states. There are four allowed charge states in D^0 and D^+ two body decays: $D^0 \to K^+\pi^-$, $D^0 \to K^0\pi^0$, $D^+ \to K^+\pi^0$ and $D^+ \to K^0\pi^+$. The four physical amplitudes, which are linear combinations of the three isospin amplitudes, obey a quadrangle relation

$$A(D^0 \to K^+ \pi^-) + \sqrt{2} A(D^0 \to K^0 \pi^0) = A(D^+ \to K^0 \pi^+) + \sqrt{2} A(D^+ \to K^+ \pi^0) \quad . \tag{6}$$

Similar quadrangle relations apply to quasi-two body decays into pairs of a vector and pseudoscalar meson:

$$\begin{aligned} A(D^0 \to K^{*+} \pi^-) + \sqrt{2} A(D^0 \to K^{*0} \pi^0) &= A(D^+ \to K^{*0} \pi^+) + \sqrt{2} A(D^+ \to K^{*+} \pi^0) \\ A(D^0 \to \rho^- K^+) + \sqrt{2} A(D^0 \to \rho^0 K^0) &= A(D^+ \to \rho^+ K^0) + \sqrt{2} A(D^+ \to \rho^0 K^+), \end{aligned} \tag{7}$$

and to partial-wave amplitudes into $K^*\rho$ states.

These quadrangle relations are quite different from the isospin triangles in CF decays. As we will see now, relations between two sides of the CF triangle (2) and two sides of the DCS quadrangle (6) follow from an approximate U-spin symmetry, thereby permiting in this approximation a triangle construction also for DCS decays. Similar relations are obeyed by S and D wave amplitudes in decays to $K^*\rho$, but do not hold for decays into a vector and a pseudoscalar meson.

A discrete U-spin symmetry transformation, interchanging d and s quarks, implies simple relations between $\Delta S = \Delta C$ and $\Delta S = -\Delta C$ processes. This transformation interchanges the four-quark $U = 1$ transition operators, $c \to su\bar{d}$ and $c \to du\bar{s}$, and implies $D^0 \leftrightarrow D^0$, $D^+ \leftrightarrow D_s^+$ and $\pi^\pm \leftrightarrow K^\pm$, $\overline{K}^0 \leftrightarrow K^0$ in initial and final states. The $\overline{K}^0\pi^0$ final state is a special case. The two pseudoscalars which are in an S-wave are in a symmetric U-spin state. The $\overline{K}^0$ is $U = 1$, while the π^0 is a combination of $U = 0$ and $U = 1$. In $D^0 \to \overline{K}^0\pi^0$ the $\Delta U = 1$ transition leads to a $U = 1$ final state to which only the $U = 0$ component of the π^0 contributes. Thus, in D^0 decay U-spin reflection implies $\overline{K}^0\pi^0 \leftrightarrow K^0\pi^0$.

A general U-spin prediction is that the ratio of every pair of U-spin related DCS and CF decay amplitudes is given by the CKM factor $V^*_{cd}V_{us}/V^*_{cs}V_{ud} = -\tan^2\theta_c$. Hence one finds

$$\begin{aligned}\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} &= \frac{A(D^0 \to K^0\pi^0)}{A(D^0 \to \overline{K}^0\pi^0)} = \frac{A(D^+ \to K^0\pi^+)}{A(D_s^+ \to \overline{K}^0K^+)} \\ &= \frac{A(D_s^+ \to K^0K^+)}{A(D^+ \to \overline{K}^0\pi^+)} = -\tan^2\theta_c \quad . \qquad (8)\end{aligned}$$

Note that this not only predicts the ratios of magnitudes for the corresponding amplitudes, but also implies equal final state phases in CF and in DCS decays. In this approximation, the quadrangle relation Eq. (6) breaks into two triangle relations

$$\begin{aligned}A(D^0 \to K^+\pi^-) + \sqrt{2}A(D^0 \to K^0\pi^0) &= A(D_s^+ \to K^0K^+) \quad , \qquad (9)\\ A(D^+ \to K^0\pi^+) + \sqrt{2}A(D^+ \to K^+\pi^0) &= A(D_s^+ \to K^0K^+) \quad . \qquad (10)\end{aligned}$$

The situation in decays to pairs of a vector and a pseudoscalar meson (VP), $D \to K^*\pi$ and $D \to \rho K$, is different. Here the two mesons in the final states are in a P-wave and both $U = 0$ and $U = 1$ components of the π^0 or ρ^0 contribute. Consequently, ratios similar to Eq. (8) do not apply to VP final states involving these neutral mesons, and the quadrangles (7) do not break into two triangles. Certain ratios of DCS to CF amplitudes are still given in the U-spin symmetry limit by $-\tan^2\theta_c$:

$$\begin{aligned}\frac{A(D^0 \to \rho^-K^+)}{A(D^0 \to K^{*-}\pi^+)} &= \frac{A(D^0 \to K^{*+}\pi^-)}{A(D^0 \to \rho^+K^-)} = \frac{A(D^+ \to \rho^+K^0)}{A(D_s^+ \to K^{*+}\overline{K}^0)} = \frac{A(D_s^+ \to K^{*+}K^0)}{A(D^+ \to \rho^+\overline{K}^0)} \\ &= \frac{A(D^+ \to K^{*0}\pi^+)}{A(D_s^+ \to \overline{K}^{*0}K^+)} = \frac{A(D_s^+ \to K^{*0}K^+)}{A(D^+ \to \overline{K}^{*0}\pi^+)} = -\tan^2\theta_c \; . \qquad (11)\end{aligned}$$

The measured value of the penultimate ratio [3]

$$\frac{|A(D^+ \to K^{*0}\pi^+)|}{|A(D_s^+ \to \overline{K}^{*0}K^+)|} = (1.41 \pm 0.37)\tan^2\theta_c \quad , \qquad (12)$$

is in agreement with this prediction at about one standard deviation.

Predictions very similar to Eq. (8) hold for ratios of the three partial wave amplitudes in decays to two vector mesons. One simply replaces $K \leftrightarrow K^*$ and $\pi \leftrightarrow \rho$, excluding final states involving ρ^0 in ratios of P-wave amplitudes. Two triangle relations similar to (9) and (10) are obeyed by S and D wave amplitudes, where the two vector mesons are in symmetric U-spin states

$$A_{S,D}(D^0 \to K^{*+}\rho^-) + \sqrt{2}A_{S,D}(D^0 \to K^{*0}\rho^0) = A_{S,D}(D_s^+ \to K^{*0}K^{*+}) \quad , (13)$$
$$A_{S,D}(D^+ \to K^{*0}\rho^+) + \sqrt{2}A_{S,D}(D^+ \to K^{*+}\rho^0) = A_{S,D}(D_s^+ \to K^{*0}K^{*+}) \quad . (14)$$

Finally, U-spin predictions can be generalized to any U-spin related pair of multi-body DCS and CF charmed meson decays. For instance, one predicts

$$\frac{A(D^+ \to K^+\pi^+\pi^-)}{A(D_s^+ \to K^+K^-\pi^+)} = -\tan^2\theta_c \quad . \tag{15}$$

The measured value of this ratio [3]

$$\frac{|A(D^+ \to K^+\pi^+\pi^-)|}{|A(D_s^+ \to K^+K^-\pi^+)|} = (1.68 \pm 0.30)\tan^2\theta_c \quad , \tag{16}$$

is 2.3σ away from this prediction. Other predictions [15], such as $A(D^+ \to K^+\pi^+\pi^-)/A(D^+ \to K^-\pi^+\pi^+) = A(D_s^+ \to K^+K^+\pi^-)/A(D_s^+ \to K^+K^-\pi^+) = -\tan^2\theta_c$, where initial and final states in DCS and CF processes are not related by U-spin, do not follow from SU(3) alone but require further dynamical assumptions.

Now let us discuss how U-spin breaking may show up in magnitudes of amplitudes and in their final state phase differences. For this matter consider, for instance, the two U-spin related triangles of Eqs. (2) and (9), where the first triangle follows from isospin symmetry while the second one holds only in the SU(3) symmetry limit. In this limit the two triangles are congruent to each other; the ratio of their corresponding sides is given by a common factor of $\tan^2\theta_c$.

In order to demonstrate the effect of SU(3) breaking on the pattern of the DCS triangle (9) relative to the CF triangle (2), it is convenient to decompose amplitudes into diagramatic contributions [4, 19]: a color favored "tree" amplitude T, a "color-suppressed" amplitude C and an "exchange" amplitude E. Thus, $\Delta S = \Delta C$ amplitudes can be expressed as

$$\begin{aligned} A(D^0 \to K^-\pi^+) &= T + E \quad , \quad \sqrt{2}A(D^0 \to \overline{K}^0\pi^0) = C - E \quad , \\ A(D^+ \to \overline{K}^0\pi^+) &= T + C \quad , \end{aligned} \tag{17}$$

while $\Delta S = -\Delta C$ amplitudes are

$$\begin{aligned} A(D^0 \to K^+\pi^-) &= -\tan^2\theta_c(T' + E') \ , \quad \sqrt{2}A(D^0 \to K^0\pi^0) = -\tan^2\theta_c(C' - E') \ , \\ A(D_s^+ \to K^0K^+) &= -\tan^2\theta_c(T' + C') \quad , \end{aligned} \tag{18}$$

where in the SU(3) limit $T' = T, C' = C, E' = E$. We stress again that Eqs. (17) and (18) are equivalent to isospin and SU(3) decompositions, respectively. The above two sets of equations provide a suitable phenomenological framework for incorporating important resonant contributions through the terms E and E' [7, 20].

A successful fit to all CF D decays to two pseudoscalars, including decays into $K\eta$ and $K\eta'$, yields [20]

$$T = 2.69 \quad , \quad C = -1.96 e^{i28^\circ} \quad , \quad E = 1.60 e^{i114^\circ} \quad , \tag{19}$$

where amplitudes are given in units of 10^{-6} GeV. The sizable magnitude of E and its large phase relative to T (chosen to be real) prove the importance of nearby resonances. The color-suppressed amplitude C acquires a smaller complex phase from rescattering through states fed by T. We note that also the exotic amplitudes $A(D^+ \to \overline{K}^0 \pi^+)$ and $A(D_s^+ \to K^0 K^+)$, which do not include resonance contributions, carry final state phases. The lengths of the three sides of the CF triangle (2) from which the amplitudes (19) were obtained [20] are

$$|T + E| = 2.50 \quad , \quad |C - E| = 2.62 \quad , \quad |T + C| = 1.36 \quad , \tag{20}$$

and the corresponding angles opposite these sides are $70^\circ, 80^\circ$ and 30°, respectively.

SU(3) breaking is introduced in T' and C' by assuming factorization and using the above mentioned value $F_0^{DK}(m_\pi^2)/F_0^{D\pi}(m_K^2) \approx F_0^{DK}(0)/F_0^{D\pi}(0) = 1.0$ [6], where a few percent correction due to an extrapolation from the measured value at $q^2 = 0$ is neglected. Thus

$$\frac{T'}{T} = \frac{f_K F_0^{D\pi}(m_K^2)(1 - m_\pi^2/m_D^2)}{f_\pi F_0^{DK}(m_\pi^2)(1 - m_K^2/m_D^2)} = 1.31 \quad , \quad \frac{C'}{C} = 1 \quad . \tag{21}$$

For the resonant contribution we assume six possible factors which cover a reasonable range of parameters: (a) $E' = 1.3E$ (b) $E' = 0.7E$ (c) $E' = 1.3 e^{i30^\circ} E$ (d) $E' = 0.7 e^{i30^\circ} E$ (e) $E' = 1.3 e^{-i30^\circ} E$ and (f) $E' = 0.7 e^{-i30^\circ} E$. A factor between 0.7 and 1.3 seems adequate for SU(3) breaking in the D^0 effective couplings to the resonances and to their charge-conjugates. This factor is real for one dominant resonance around 1800-1900 MeV [7], for which the common phase of E and E' depends only on the resonance mass and width. The contribution from the more distant resonance at 1430 MeV was estimated [7] to be at least a factor two smaller. Even in case that the phase of this contribution is 90° relative to the dominant one, it may change the phase of E' relative to E by no more than 30° which we consider as extreme cases.

The resulting lengths of sides and the angles in the $\Delta S = -\Delta C$ triangle are shown in Table 1. The four values of $|T' + E'|/|T + E|$ in cases (a)$-$(d) are consistent with the recent measurement (1) at one standard deviation, whereas the values (e) and (f) corresponding to a negative SU(3) breaking phase between E and E' are excluded by the data at a high level of confidence. In the four cases which are consistent with data the angles opposite the three sides $T' + E'$, $C' - E'$ and $T' + C'$ are (a) $80^\circ, 63^\circ, 37^\circ$ (b) $96^\circ, 46^\circ, 38^\circ$ (c) $64^\circ, 61^\circ, 55^\circ$ and (d) $91^\circ, 41^\circ, 48^\circ$. Comparing this with the above-mentioned angles of the CF triangle, we see that final state phase patterns in DCS and CF amplitude triangles can be quite different. Within the above range of SU(3) breaking parameters corresponding angles in the two triangles differ by as much as 39°.

An interesting quantity is the final state phase difference $\delta = \arg[(T' + E')/(T + E)]$ between $A(D^0 \to K^+\pi^-)$ and $A(D^0 \to K^-\pi^+)$, which vanishes in the U-spin

Table I: Sides and opposite angles of amplitude triangles. See text for units. First line denotes $\Delta S = \Delta C$ triangle (2); other lines denote $\Delta S = -\Delta C$ triangles (9).

E'/E (case)	$T+E$ or $T'+E'$ Side	Angle	$C-E$ or $C'-E'$ Side	Angle	$T+C$ or $T'+C'$ Side	Angle
CF triangle	2.50	70°	2.62	80°	1.36	30°
(a) 1.3	3.28	80°	2.96	63°	2.02	37°
(b) 0.7	3.23	96°	2.32	46°	2.02	38°
(c) $1.3e^{i30^\circ}$	2.21	64°	2.14	61°	2.02	55°
(d) $0.7e^{i30^\circ}$	2.70	91°	1.78	41°	2.02	48°
(e) $1.3e^{-i30^\circ}$	4.28	96°	3.57	56°	2.02	28°
(f) $0.7e^{-i30^\circ}$	3.81	105°	2.75	44°	2.02	31°

symmetry limit and which plays an important role in studies of $D^0 - \overline{D}^0$ mixing as mentioned in the introduction. This phase is found to be 0, -17, -2 and -22 degrees in cases (a) (b) (c) and (d), respectively. It can be positive if SU(3) breaking enhances E' more than T'. Crudely speaking, very different shapes of the CF and DCS triangles would be evidence for a large value of $|\delta|$. The magnitude of this phase grows with an increasing difference between the two angles opposite $C-E$ and $C'-E'$. In cases (b) and (d), where this angle difference is 34° and 39°, δ is -17° and -22°, respectively, about half of this angle difference. The other $17^\circ = \mathrm{Arg}[(T'+C')/(T+C)]$ are due to a phase difference between the exotic amplitudes $A(D_s^+ \to K^0 K^+)$ and $A(D^+ \to \overline{K}^0 \pi^+)$. We note that very large values of δ, around 45° or larger as envisaged in [12], cannot be accommodated in our scheme within a reasonable range of SU(3) breaking parameters. Such values would require an SU(3) breaking factor of 2.5 in E'/E.

Finally, we make a few comments on the difficulty of measuring two of the amplitudes in Eq. (9). There is no way to distinguish a K^0 from a $\overline{K}^0$ when it is detected as a K_S. In CF decays one simply *assumes* the flavor of a neutral kaon which is an adequate approximation. This would be clearly wrong for DCS decays. Tagging the flavor of a K^0 through the charged lepton ℓ^+ in semileptonic decays requires looking at decay times less than a few K_S lifetimes, before the K_S has decayed away. This reduces the rate by a large factor and does not seem feasible for rare DCS decays.

Alternatively, one may measure the triangles (13) describing DCS decays to two vector mesons in S and D waves, where $K^{*0} \to K^+\pi^-$ identifies the flavor of the neutral K^*. The structure of these triangles could then be compared with those of (5) for S and D waves. This requires a partial wave analysis through angular distributions of decay products. Such analysis was performed in CF decays [21], where evidence was found for negligible P-wave amplitudes.

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